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OFF THE MASS SHELL: ELECTROWEAK PHYSICS AT NUTEV

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ABSTRACT

The NuTeV collaboration has performed precision measurements of the ratio of neutral current to charged current cross-sections in high rate, high energy neutrino and anti-neutrino beams on a dense, primarily steel, target. The separate neutrino and anti-neutrino beams, high statistics, and improved control of other experimental systematics, allow the determination of electroweak parameters with significantly greater precision than past νN scattering experiments. Our null hypothesis test of the standard model prediction measures $\sin^2\theta_W^{(\text{on-shell})} = 0.2277 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst})$, a value which is 3.0σ above the prediction. We discuss possible explanations for and implications of this discrepancy.

1 Introduction and Motivation

Neutrino scattering played a key role in establishing the structure of the standard model of electroweak unification, and it continues to be one of the most precise probes of the weak neutral current available experimentally today. With copious data from the production and decay of on-shell Z and W bosons for comparison, contemporary neutrino scattering measurements serve to validate the theory over many orders of magnitude in momentum transfer and provide one of the most precise tests of the weak couplings of neutrinos. In addition, precise measurements of weak interactions far from the boson poles are inherently sensitive to processes beyond our current knowledge, including possible contributions from leptoquark and Z' exchange[1] and new properties of neutrinos themselves[2].

The Lagrangian for weak neutral current ν–q scattering can be written as

$$\begin{aligned} \mathcal{L} &= -\frac{G_F\rho_0}{\sqrt{2}}(\overline{\nu}\gamma^\mu(1-\gamma^5)\nu) \\ &\quad \times \left(\epsilon_L^q\overline{q}\gamma_\mu(1-\gamma^5)q + \epsilon_R^q\overline{q}\gamma_\mu(1+\gamma^5)q\right), \end{aligned} \tag{1}$$

where deviations from $\rho_0 = 1$ describe non-standard sources of SU(2) breaking, and $\epsilon_{L,R}^q$ are the chiral quark couplings [1] For the weak charged current, $\epsilon_L^q = I_{\text{weak}}^{(3)}$ and $\epsilon_R^q = 0$, but for the neutral current ϵ_L^q and ϵ_R^q each contain an additional term, $-Q\sin^2\theta_W$, where Q is the quark's electric charge in units of e.

The ratio of neutral current to charged current cross-sections for either ν or $\overline{\nu}$ scattering from isoscalar targets of u and d quarks can be written as[3]

$$R^{\nu(\overline{\nu})} \equiv \frac{\sigma(\overset{(-)}{\nu}\, N \to \overset{(-)}{\nu}\, X)}{\sigma(\overset{(-)}{\nu}\, N \to \ell^{-(+)}X)} = (g_L^2 + r^{(-1)}g_R^2), \tag{2}$$

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[1]Note that although we use a process-independent notation here for a tree-level ρ, radiative corrections to ρ depend slightly on the particles involved in the weak neutral interaction. In this case, $\rho \equiv \sqrt{\rho^{(\nu)}\rho^{(q)}}$.

where

$$r \equiv \frac{\sigma(\overline{\nu}N \to \ell^+ X)}{\sigma(\nu N \to \ell^- X)} \sim \frac{1}{2}, \tag{3}$$

and $g_{L,R}^2 = (\epsilon_{L,R}^u)^2 + (\epsilon_{L,R}^d)^2$. Many corrections to Equation 2 are required in a real target[4], but those most uncertain result from the suppression of the production of charm, which is the CKM-favored final state for charged-current scattering from the strange sea. One way to reduce this source of uncertainty on electroweak parameters is to measure the observable

$$\begin{aligned} R^- &\equiv \frac{\sigma(\nu_\mu N \to \nu_\mu X) - \sigma(\overline{\nu}_\mu N \to \overline{\nu}_\mu X)}{\sigma(\nu_\mu N \to \mu^- X) - \sigma(\overline{\nu}_\mu N \to \mu^+ X)} \\ &= \frac{R^\nu - rR^{\overline{\nu}}}{1-r} = (g_L^2 - g_R^2), \end{aligned} \tag{4}$$

first suggested by Paschos and Wolfenstein[5] and valid under the assumption of equal momentum carried by the u and d valence quarks in the target. Since $\sigma^{\nu q} = \sigma^{\overline{\nu}\,\overline{q}}$ and $\sigma^{\overline{\nu}q} = \sigma^{\nu\overline{q}}$, the effect of scattering from sea quarks, which are symmetric under the exchange $q \leftrightarrow \overline{q}$, cancels in the difference of neutrino and anti-neutrino cross-sections. Therefore, the suppressed scattering from the strange sea does not cause large uncertainties in R^-. R^- is more difficult to measure than R^ν, primarily because the neutral current scatterings of ν and $\overline{\nu}$ yield identical observed final states which can only be distinguished through *a priori* knowledge of the initial state neutrino.

The experimental details and theoretical treatment of cross-sections in the NuTeV electroweak measurement are described in detail elsewhere[4]. In brief, we measure the experimental ratio of neutral current to charged current candidates in both a neutrino and anti-neutrino beam. A Monte Carlo simulation is used to express these experimental ratios in terms of fundamental electroweak parameters. This procedure implicitly corrects for details of the neutrino cross-sections and experimental backgrounds. For the measurement of $\sin^2\theta_W$, the sensitivity arises in the ν beam, and the measurement in the $\overline{\nu}$ beam is the control sample for systematic uncertainties, as suggested in the Paschos-Wolfenstein R^- of Eqn. 4. For simultaneous fits to two electroweak parameters, e.g., $\sin^2\theta_W$ and ρ or left and right handed couplings, this redundant control of systematics cannot be realized.

2 Result

As a test of the electroweak predictions for neutrino nucleon scattering, NuTeV performs a single-parameter fit to $\sin^2\theta_W$ with all other parameters assumed to have their standard values, e.g., standard electroweak radiative corrections with $\rho_0 = 1$. This fit determines

$$\begin{aligned} \sin^2\theta_W^{(\text{on-shell})} &= 0.22773 \pm 0.00135(\text{stat.}) \pm 0.00093(\text{syst.}) \\ &- 0.00022 \times (\frac{M_{\text{top}}^2 - (175\text{ GeV})^2}{(50\text{ GeV})^2}) \\ &+ 0.00032 \times \ln(\frac{M_{\text{Higgs}}}{150\text{ GeV}}). \end{aligned} \quad (5)$$

The small dependences in M_{top} and M_{Higgs} result from radiative corrections as determined from code supplied by Bardin[6] and from V6.34 of ZFITTER[7]; however, it should be noted that these effects are small given existing constraints on the top and Higgs masses[8]. A fit to the precision electroweak data, excluding neutrino measurements, predicts a value of 0.2227 ± 0.00037[8, 9], approximately 3σ from the NuTeV measurement. Interpretations of the NuTeV data in terms of M_W and ρ_ν and model-independent neutrino-quark chiral couplings are discussed elsewhere [4, 10].

3 Interpretation

The NuTeV $\sin^2\theta_W$ result is approximately three standard deviations from the prediction of the standard electroweak theory. This by itself is surprising; however, it is not immediately apparent what the cause of this discrepancy might be. We discuss, in turn, the possibility that the NuTeV result is a statistical fluctuation among many precision results, the possibility that unexpected quark flavor asymmetries or nuclear effects influence the result, and finally possibilities for non-standard physics which could be appearing in the anomalous NuTeV value.

3.1 Significance in a Global Context

For fits assuming the validity of the standard model, it is appropriate to consider the *a priori* null hypothesis test chosen in the proposal of the NuTeV experiment, namely the measurement of $\sin^2\theta_W^{(\text{on-shell})}$. The fit to precision data, including NuTeV, performed by the LEPEWWG has a global the global χ^2 of 28.8 for 15 degrees of freedom[8, 9], including significant contributions from NuTeV's $\sin^2\theta_W$ measurement and $A_{FB}^{0,b}$ from LEP I. The probability of the fit χ^2 being above 28.8 is 1.7%. Without NuTeV, this probability of the resulting χ^2 is a plausible 14%. This suggests that in the context of all the precision data, as compiled by the LEPEWWG, the NuTeV result is still a statistical anomaly sufficient to spoil, or at least sully, the fit within the standard model.

This large χ^2 is dominated by two moderately discrepant measurements, namely $A_{FB}^{0,b}$ and the NuTeV $\sin^2\theta_W$, and if one or both are discarded arbitrarily, then the data is reasonably consistent with the standard model. However, the procedure of merely discarding one or both of these measurements to make the fit "work" is clearly not rigorous. Furthermore, the potential danger of such a procedure has been noted previously in the literature. For example, if $A_{FB}^{0,b}$ were disregarded, then the most favored value of the Higgs mass from the fit would be well below the direct search limits. Constraining the fit to be consistent with mass limits from standard model Higgs boson searches results in still uncomfortably large χ^2[11].

3.2 Unexpected QCD Effects

As noted above, corrections to Eqns. 2 and 4 are required to extract electroweak parameters from neutrino scattering on the NuTeV target. In particular, these equations assume targets symmetric under the exchange of u and d quarks, and that quark seas consist of quarks and anti-quarks with identical momentum distributions.

The NuTeV analysis corrects for the significant asymmetry of d and u quarks that arises because the NuTeV target, which is primarily composed of iron, has an $\approx 6\%$ fractional excess of neutrons over protons. However, this correction is exact only with the assumption of isospin symmetry, i.e., $\overset{(-)}{u}_p(x) = \overset{(-)}{d}_n(x)$, $\overset{(-)}{d}_p(x) = \overset{(-)}{u}_n(x)$. This assumption, if significantly incorrect, could produce a sizable effect in the NuTeV extraction of $\sin^2\theta_W$[12, 13, 14, 15].

Dropping the assumptions of symmetric heavy quark seas, isospin symmetry and a target symmetric in neutrons and protons, but assuming small deviations in all cases, we calculate the effect of these deviations on R^- is[16]:

$$\begin{aligned}\delta R^- \approx\ & +\delta N\left(\frac{U_p - D_p}{U_p + D_p}\right)(3\Delta_u^2 + \Delta_d^2) \\ & + \frac{(U_p - \overline{U}_p - D_n + \overline{D}_n) - (D_p - \overline{D}_p - U_n + \overline{U}_n)}{2(U_p - \overline{U}_p + D_p - \overline{D}_p)}(3\Delta_u^2 + \Delta_d^2) \\ & + \frac{S_p - \overline{S}_p}{U_p - \overline{U}_p + D_p - \overline{D}_p}(2\Delta_d^2 - 3(\Delta_d^2 + \Delta_u^2)\epsilon_c), \end{aligned} \quad (6)$$

where $\Delta_{u,d}^2 = (\epsilon_L^{u,d})^2 - (\epsilon_R^{u,d})^2$, Q_N is the total momentum carried by quark type Q in nucleon N, and the neutron excess, $\delta N \equiv A - 2Z/A$. ϵ_c denotes the ratio of the scattering cross section from the strange sea including kinematic suppression of heavy charm production to that without kinematic suppression. The first term is the effect of the neutron excess, which is accounted for in the NuTeV analysis; the second is the effect of isospin violation and the third is the effect of an asymmetric strange sea.

NuTeV does not exactly measure R^{-}, in part because it is not possible experimentally to measure neutral current reactions down to zero recoil energy. To parameterize the exact effect of the symmetry violations above, we have numerically evaluated the effects on the NuTeV results of isospin and $s-\overline{s}$ asymmetries as a function of x [16]. This analysis shows that the level of isospin violation required to shift the $\sin^2\theta_W$ measured by NuTeV to its standard model expectation would be, e.g., $D_p - U_n \sim 0.01$ (about 5% of $D_p + U_n$), and that the level of asymmetry in the strange sea required would be $S - \overline{S} \sim +0.007$ (about 30% of $S + \overline{S}$).

3.2.1 Isospin Violations

Several recent classes of non-perturbative models predict isospin violation in the nucleon[12, 13, 14]. The earliest estimation in the literature, a bag model calculation[12], predicts large valence asymmetries of opposite sign in $u_p - d_n$ and $d_p - u_n$ at all x, which would produce a shift in the NuTeV $\sin^2\theta_W$ of -0.0020. However, this estimate neglects a number of effects, and a complete bag model calculation by Rodionov *et al.* [13] conclude that asymmetries at very high x are larger, but the asymmetries at moderate x are smaller and even of opposite sign at low x, thereby reducing the shift in $\sin^2\theta_W$ to a negligible -0.0001. Finally, the effect is also evaluated in the meson cloud model[14], and there the asymmetries are much smaller at all x, resulting in a modest shift in the NuTeV $\sin^2\theta_W$ of $+0.0002$.

Models aside, the NuTeV data itself cannot provide a significant independent constraint on this form of isospin violation. However, because PDFs extracted from neutrino data (on heavy targets) are used to separate sea and valence quark distributions which affect observables at hadron colliders[17], global analyses of PDFs including the possibility of isospin violation may be able to constrain this possibility experimentally. At least one author[18] has begun to consider the experimental isospin constraints in the context of “nuclear PDFs”, and found very small isospin effects, except at very high x and low Q^2, a region removed by the visible energy requirement ($E_{\mathrm{calorimeter}} > 20$ GeV) of the NuTeV analysis.

3.2.2 Strange Sea Asymmetry

If the strange sea is generated by purely perturbative QCD processes, then neglecting electromagnetic effects, one expects $\langle s(x)\rangle = \langle \overline{s}(x)\rangle$. However, it has been noted that non-perturbative QCD effects can generate a significant momentum asymmetry between the strange and anti-strange seas[19].

By measuring the processes $\nu_N, \overline{\nu}_N \rightarrow \mu^+\mu^- X$ the CCFR and NuTeV experiments constrain the difference between the momentum distributions of the strange and anti-strange seas. Within the NuTeV cross-section model, this data implies a *negative* asymmetry[16],

$$S - \overline{S} = -0.0027 \pm 0.0013, \tag{7}$$

or an asymmetry of $11 \pm 6\%$ of $(S + \overline{S})$. Therefore, dropping the assumption of strange-antistrange symmetry results in an *increase* in the NuTeV value of $\sin^2\theta_W$,

$$\Delta \sin^2\theta_W = +0.0020 \pm 0.0009. \tag{8}$$

The initial NuTeV measurement, which assumes $\langle s(x)\rangle = \langle \overline{s}(x)\rangle$, becomes

$$\sin^2\theta_W^{(\mathrm{on-shell})} = 0.2297 \pm 0.0019.$$

Hence, if we use the experimental measurement of the strange sea asymmetry, the discrepancy with the standard model is increased to 3.7σ significance.

3.2.3 Nuclear Effects

Nuclear effects which can be absorbed into process-independent PDFs will not affect the NuTeV result. However, several authors have recently explored the possibility that neutrino neutral and charged current reactions may see different nuclear effects and therefore influence the NuTeV result.

A recent comment in the literature[20] has offered a Vector Meson Dominance (VMD) model of low x shadowing in which such an effect might arise. The most precise data that overlaps the low x and Q^2 kinematic region of NuTeV comes from NMC[21], which observed a logarithmic Q^2 dependence of the shadowing effect as predicted by perturbative QCD for Q^2 independent shadowing as in Pomeron models. However, models with a mixture of VMD and Pomeron shadowing can be consistent with this high Q^2 data [22, 23].

The NuTeV analysis, which uses ν and $\overline{\nu}$ data at $< Q^2 >$ of 25 and 16 GeV^2, respectively, is far away from the VMD regime, and the effect of this VMD model is significantly smaller than stated in Ref. [20]. The most serious flaw in the hypothesis that this accounts for the NuTeV result, however, is that it is not internally consistent with the NuTeV data. Shadowing, a low x phenomenon, largely affects the sea quark distributions which are common between ν and $\overline{\nu}$ cross-sections, and therefore cancel in R^-. However, the effects in R^ν and $R^{\overline{\nu}}$ individually are much larger than in R^- and this model *increases* the prediction for NuTeV's R^ν and $R^{\overline{\nu}}$ by 0.6% and 1.2%, respectively. NuTeV's R^ν and $R^{\overline{\nu}}$ are both below predictions and the significant discrepancy is in the ν mode, not the $\overline{\nu}$ "control" sample, both in serious contradiction with the prediction of the VMD model.

Another recent paper[24] has suggested that there may be little or no EMC effect in the neutrino charged-current but the expected EMC effect suppression at high x in the neutral current. If true, this could have the right behavior and perhaps magnitude to explain the NuTeV data because of the effect at high x. Unfortunately, this mechanism would cause large differences between F_2^ν and F_2^ℓ on heavy targets at high x which are excluded by the CCFR charged-current cross-section measurements[25].

3.3 New Physics

The primary motivation for embarking on the NuTeV measurement was the possibility of observing hints of new physics in a precise measurement of neutrino-nucleon scattering. NuTeV is well suited as a probe of non-standard physics for two reasons. First, the precision of the measurement is a significant improvement, most noticeably in systematic uncertainties, over previous measurements. Second, NuTeV's measurement has unique sensitivity to new processes when compared to other precision data. In particular, NuTeV probes weak processes far off-shell, and thus is sensitive to other tree level processes involving exchanges of heavy particles. Also, the initial state particle is a neutrino, and neutrino couplings are the most poorly constrained by the Z^0 pole data, since they are primarily accessed via the measurement of the Z invisible width.

In considering models of new physics, a "model-independent" effective coupling measurement [4, 10] is the best guide for evaluating non-standard contributions to the NuTeV measurements. This measurement suggests a large deviation in the left-handed chiral coupling to the target quarks, while the right-handed coupling is as expected. Such a pattern of changes in couplings is consistent with either a hypothesis of loop corrections that affect the weak process itself or another tree level contribution that contributes primarily to the left-handed coupling. Chiral coupling deviations are often parameterized in terms of the mass scale for a unit-coupling "contact interaction" in analogy with the Fermi effective theory of low-energy weak interactions. Assuming a contact interaction described by a Lagrangian of the form

$$-\mathcal{L} = \sum_{H_q \in \{L,R\}} \frac{\pm 4\pi}{\left(\Lambda^{\pm}_{LH_q}\right)^2} \times \left\{\overline{l_L}\gamma^\mu l_L \overline{q_{H_q}}\gamma_\mu q_{H_q} + l_L\gamma^\mu \overline{l_L}\,\overline{q_{H_q}}\gamma_\mu q_{H_q} + \text{C.C.}\right),$$

the NuTeV result can be explained by an interaction with mass scale $\Lambda_{LL}^{+} \approx 4 \pm 0.8$ TeV.

3.3.1 Extra U(1) Interaction

Phenomenologically, an extra $U(1)$ gauge group which gives rise to interactions mediated by a heavy Z' boson, $m_{Z'} \gg m_Z$, is an attractive model for new physics. In general, the couplings associated with this new interaction are arbitrary, although specific models in which a new $U(1)$ arises may provide predictions or ranges of predictions for these couplings. An example of such a model is an $E(6)$ gauge group, which encompasses the $SU(3)\times SU(2)\times U(1)$ of the standard model and also predicts several additional $U(1)$ subgroups which lead to observable interactions mediated by Z' bosons. Before the NuTeV measurement, several authors had suggested in the literature that the other precision electroweak data favored the possibility of a Z' boson[26, 27].

We have analyzed the effect of Z's in $E(6)$ GUT models[1, 28] on the NuTeV measurement of the chiral couplings. The effect of these bosons when the Z and Z' do not mix is primarily on the right-handed coupling. It is possible to reduce the left-handed coupling somewhat by allowing $Z-Z'$ mixing; however, this possibility is severely constrained by precision data at the Z^0 pole[27].

A Z' with coupling magnitudes equal to those of the Z (Z'_{SM}) but leading to a destructive interference with the Z exchange could explain the NuTeV measurement if the Z' mass were in the range $\approx$ 1–1.5 TeV. Current limits from the TeVatron experiments on such Z'_{SM} are approximately 0.7 TeV[29]. Several authors have also recently discussed other $U(1)$ extensions in the context of the NuTeV result and found significant effects[15, 30].

3.3.2 Anomalous Neutrino Neutral Current

There are few precision measurements of neutrino neutral current interactions. Measurements of neutrino-electron scattering from the CHARM II experiment[31] and the direct measurement of $\Gamma(Z \to \nu\overline{\nu})$ from the observation of $Z \to \nu\overline{\nu}\gamma$ at the Z^0 pole[8] provide measurements of a few percent precision. The two most precise measurements come from the inferred Z invisible width[8] and NuTeV. As is shown in Figure 1, both of the precise rate measurements are significantly below the expectation. Theoretically, such a deviation is difficult to accomodate. One idea is a mixing of the light neutrinos with another heavy gauge singlet, but this mechanism leads to effects in *both* $Z\nu\overline{\nu}$ and $W\ell\nu$ vertices[15]. However, Takeuchi and collaborators

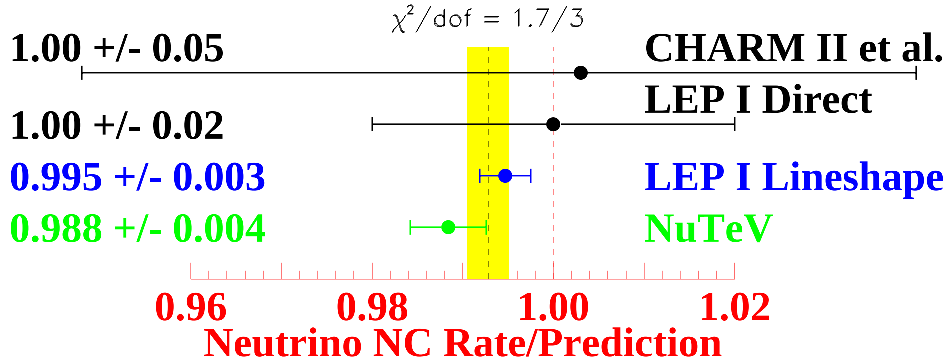

Figure 1: *Measurements of the neutrino current coupling, interpreted as a neutrino neutral current interaction rate ($\propto \rho^{(\nu)}$). The precise measurements, $\Gamma(Z \to \nu\overline{\nu})$ at LEP I and the NuTeV data, interpreted as an overall deviation in the strength of the neutral current coupling to neutrinos, are both below expectation.*

recently suggested that both of these effects could be accomodated in the precision electroweak data if the Higgs boson were heavy[32].

4 Summary

The NuTeV experiment has performed a measurement of $\sin^2\theta_W$, and finds a deviation of three standard deviations from the null hypothesis which assumes the validity of the standard model of electroweak interactions. Motivated by the significance of this discrepancy, we study both conventional and new physics explanations. Several possibilities exist, although none is theoretically compelling or has sufficient independent supporting evidence to be a clear favorite. Therefore, this result remains a puzzle.

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